Jet Propulsion Laboratory
California Institute of Technology

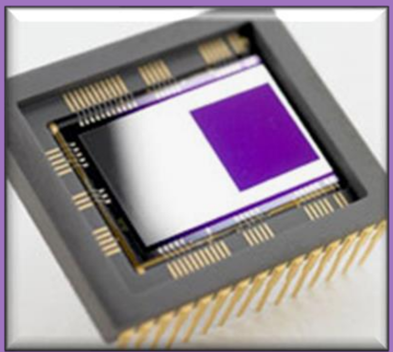
Coronagraph Camera Modeling

Patrick Morrissey
Flight Instrument Detectors and Camera Systems
Section 389N

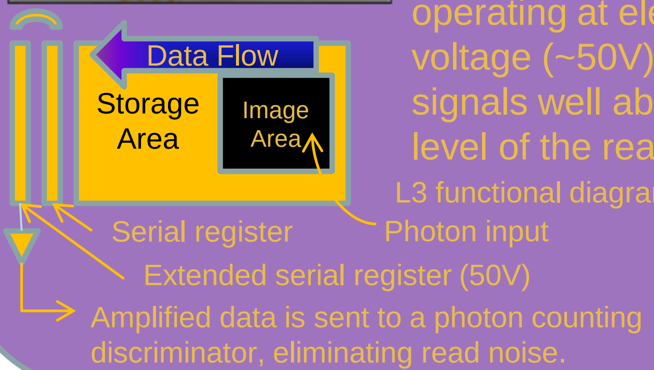
30-31 May 2018

The EMCCD – How it works

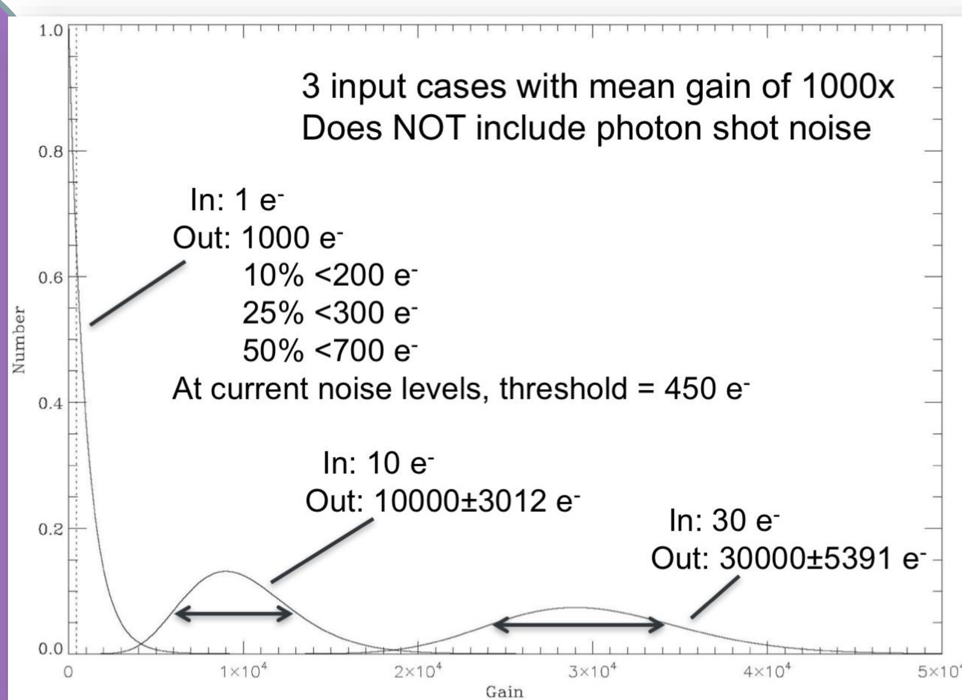
e2v L3 Technology

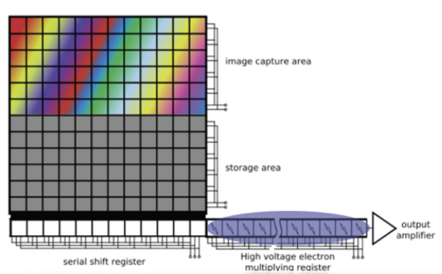


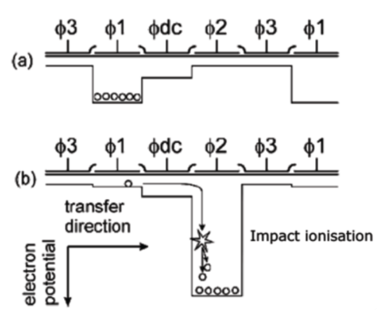
- New technology from e2v enables high QE CCD imaging and **zero read noise** photon counting.
- A **Low Light Level (L3) extended serial register** operating at elevated voltage (~50V) amplifies signals well above the level of the read noise.



L3 functional diagram







The ability of the EMCCD to transfer single electron charges, coupled with internal gain enables a high speed readout with zero read noise.

EMCCD Operational Modes

One distinguishing feature of the EMCCD is that by adjusting the HV level and readout speed, a wide range of input flux can be accommodated. Consider the following four modes:

1. **Photon counting:** In this mode, all pulses greater than the 5σ threshold are presumed to have originated from 1 electron, no matter how large.
   - High gain (>3000x)
   - Zero read noise, effectively
   - Reduced "dQE" compared to conventional CCD due to threshold and other losses
2. **Analog mode:** In this mode (think LOWFS), multiple electrons are allowed to accumulate in image pixels. The resulting amplified image is divided by the mean gain to estimate the number of electrons per pixel
   - Moderate gain (10-1000x)
   - Read noise is reduced by a factor of the mean gain but not zero
   - Incurs an "extra noise" penalty due to uncertainty in the gain register output
   - dQE can be thought of as ½ conventional CCD due to extra noise penalty
3. **Conventional fast mode:** In this mode, there is no gain and the CCD is read out at 10 MHz, which is the photon counting readout speed
   - Generally badly read noise dominated (100e-/read)
   - High dQE
4. **Conventional slow mode:** In this mode, the EMCCD conventional amplifier is used at a slow readout rate to minimize read noise with no gain.
   - Still badly read noise dominated (10e-/read) compared to modes with gain.
   - Since there is no shutter, the 3-10 second readout may be problematic
   - **There is currently no requirement to retain this mode.**

A specific EMCCD mode should be associated with every CONOPS activity

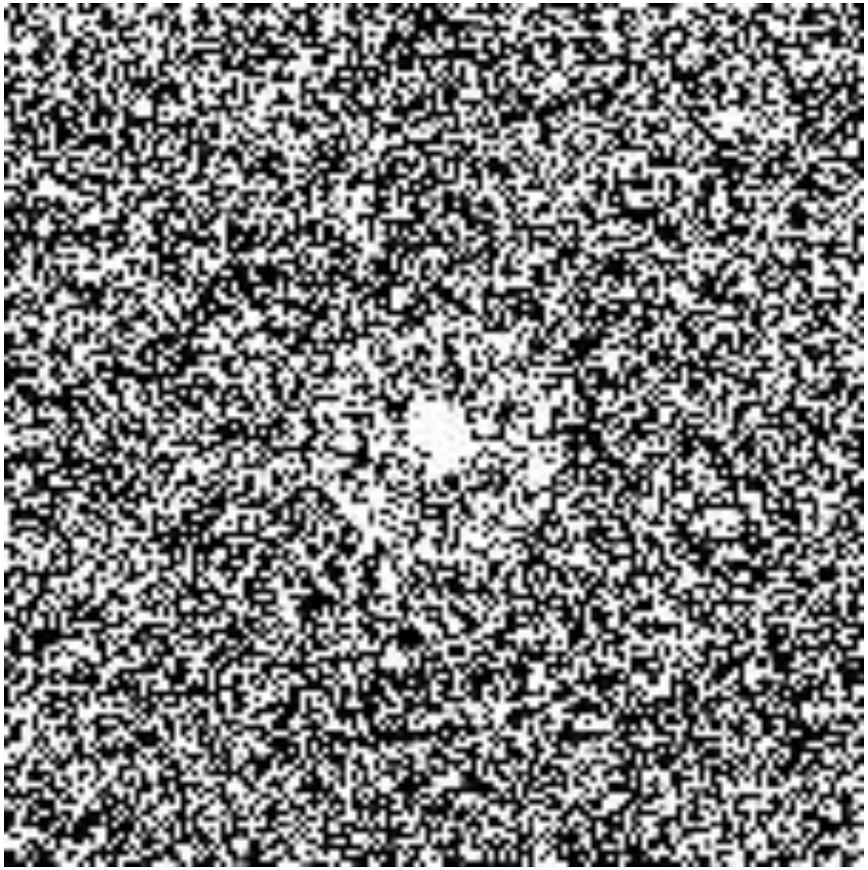
Fundamental EMCCD Noise Sources

- **Read noise:** The EMCCD does away with the primary error source of the ordinary CCD, which is read noise. Any application for which you would consider photon counting is by definition difficult or impossible to detect in the presence of read noise.
  - Remember the "miracle of the CCD." Single electrons can be transported noiselessly across thousands of CCD pixels (only to be obscured by read noise at the last step). Photon counting relies on this capability.
- **Clock Induced Charge (CIC):** Large voltages and fast clock edges can accelerate signal charges during transport and generate additional noise electrons as a result. The dominant source of CIC is the serial gain register with its large voltages. By nature, CIC occurs on a **per frame** basis, therefore there is a preference to read the array as infrequently as possible. Typical CIC is 0.005 e/pix/frame for a new device.
- **Dark current:** The thermal production of charge in silicon is greatly reduced by operating at low temperatures. Dark current is generally observed to bottom out around -100C. By the same token, the ability of the CCD to transport charge begins to degrade at low temperatures, and therefore we operate as warm as possible while minimizing dark current. In the case of a new EMCCD, **a typical value is 0.1 e/pix/hour.**
- **Extra noise:** In non-photon counting mode with gain ("analog mode"), there is an ambiguity in the number of electrons for a given pulse height. This ambiguity effectively increases the noise by **root 2** compared to photon counting mode

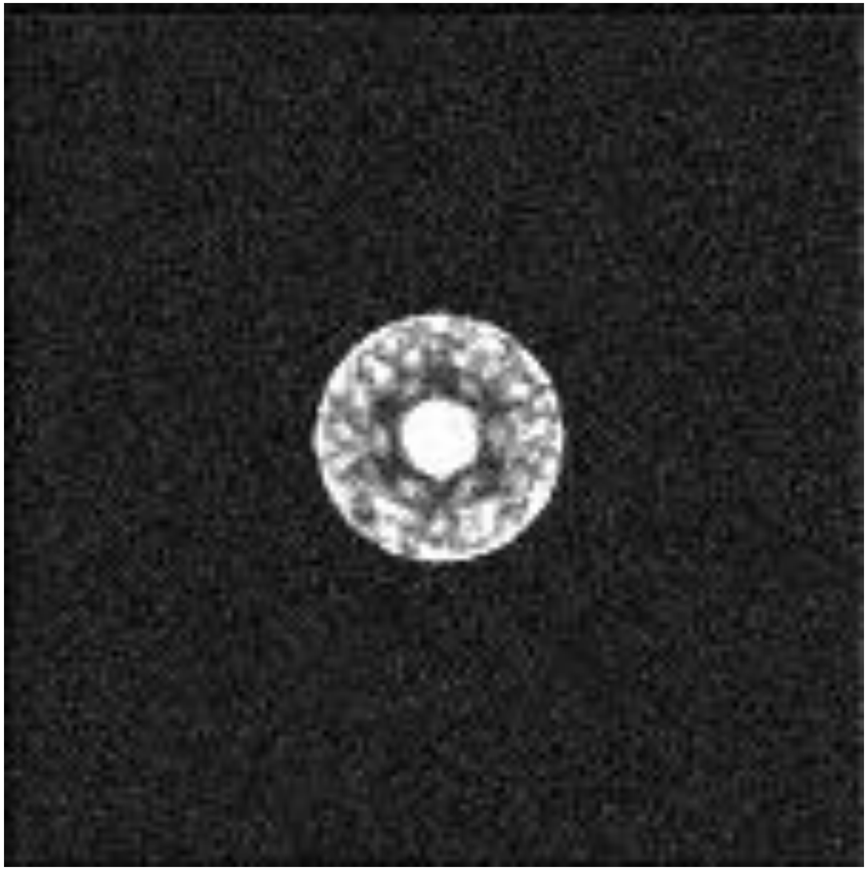
Conventional vs Photon Counting

150x150 DI array. 12 hours, 80s frames,
Speckle ~ 5 c-px^{-1}-hr^{-1}

10e^{-} RN Slow Scan Readout Gain=1



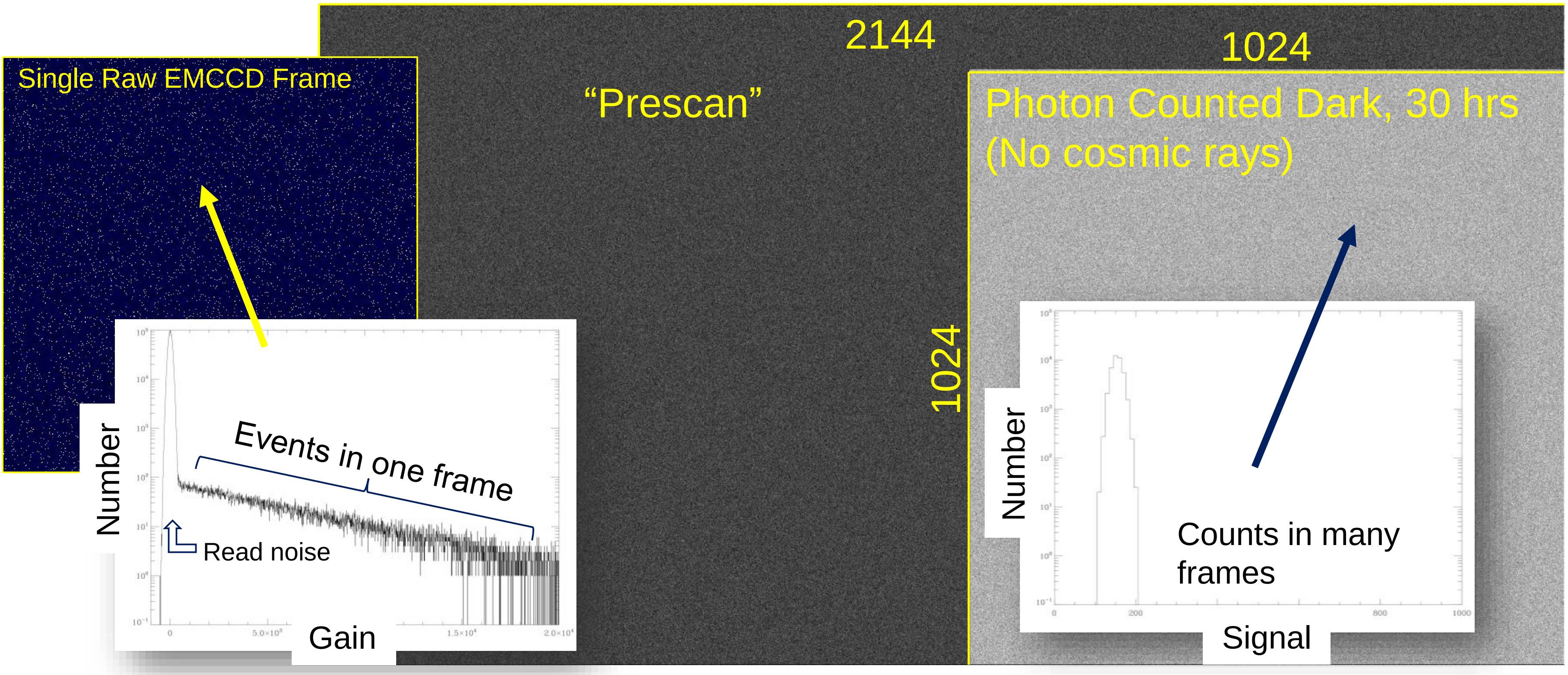
100e^{-} RN Fast Scan Readout Gain=4000



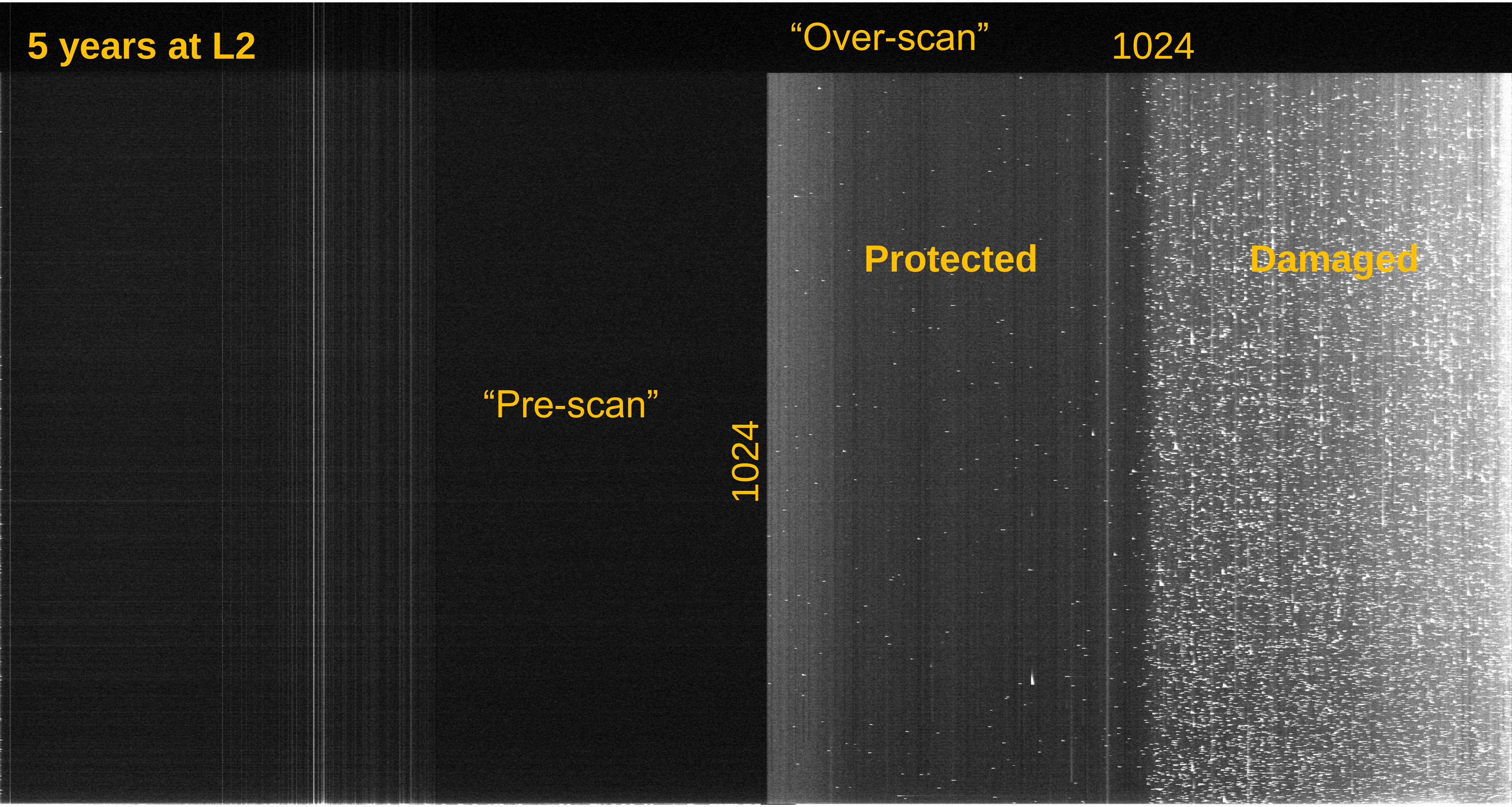
Simulations generated by mkemccd

mkemccd: detector noise simulation SW

- We have developed a piece of IDL code called mkemccd (“make emccd”) that takes as input an image in units of counts per second and returns a frame of emccd data at the specified gain and frame time
- The code includes: dark, CIC, read noise, cosmic rays and hot pixels. It also properly handles the pulse height distribution for photon counting or analog mode.
- The code has been distributed to the IM team at JPL and the IFS team at GSFC.



A Real EMCCD PC Image

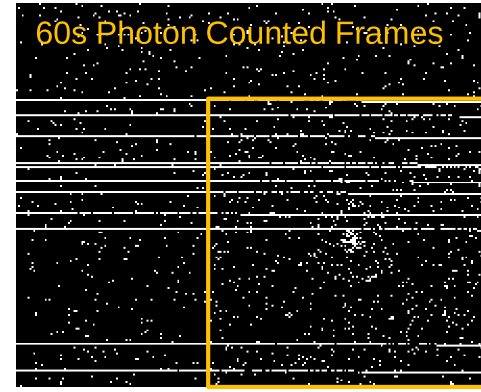


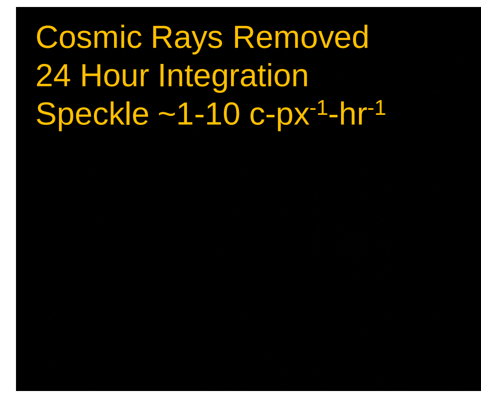
Jet Propulsion Laboratory
California Institute of Technology

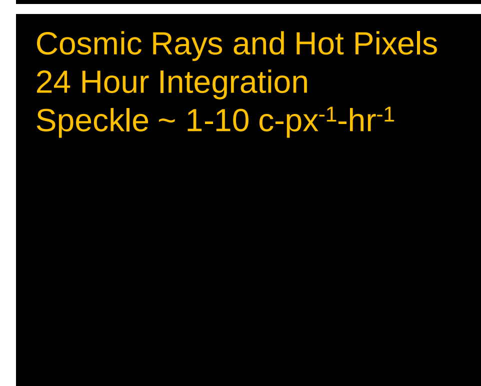
mkemccd Simulations

- **Direct Imaging EMCCD simulation.**
  - 150x150 pixels plus prescan and overscan
  - Speckle simulation provided by J. Krist and scaled to a typical (IFS-like) rate 1-10 c-px^{-1}-hr^{-1}. The central peak is several hundred c-px^{-1}-hr^{-1} and saturates.
  - Frames are generated with and without cosmic rays every 60s.
  - A simple 5σ threshold is used to identify photon events
- **Cosmic rays are a significant background if not removed, however they are easy to find.**
  - In this simulation, the combined backgrounds are about 1.7 c-px^{-1}-hr^{-1} without and 5 c-px^{-1}-hr^{-1} with cosmic rays (~3x).

Parameter	Value
Gain	4000x
Speckle	1-10 c-px^{-1}-hr^{-1}
Dark	0.5 c-px^{-1}-hr^{-1}
CIC	0.025 c-px^{-1}-fr^{-1}
Read Noise	100e^{-}
Cosmic Rays	5 cm^{-2}-s^{-1}
Hot Pixels	5 c-px^{-1}-hr^{-1}
Frame time	60s







Jet Propulsion Laboratory
California Institute of Technology

EMCCD Mode Calculator

Latest Version: 180504

EMCCD Band 3 IFS SNR Mode Calculator

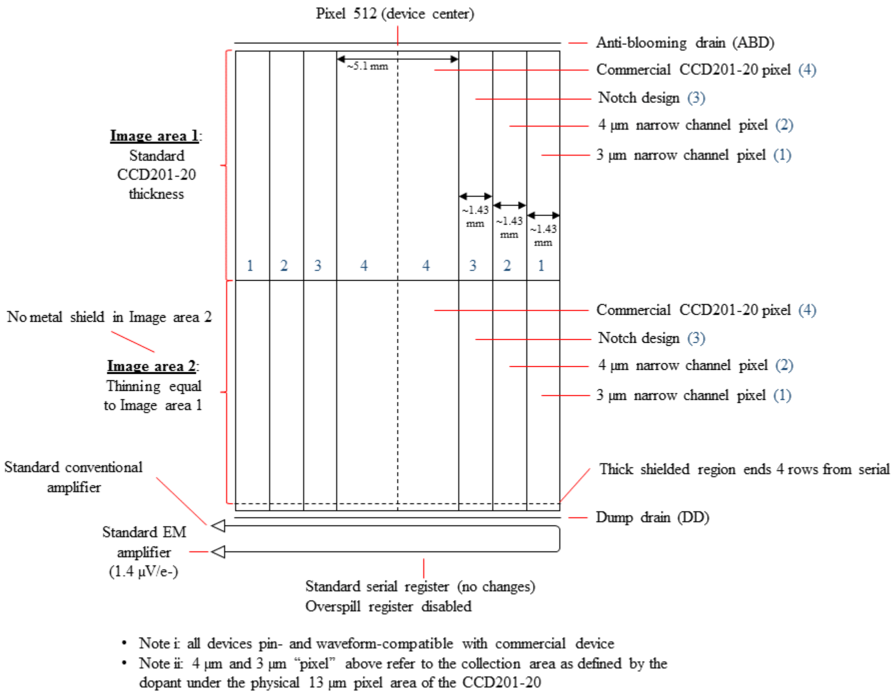
	BOL	EOL		
Speckle rate	0.009		ph/s/psf	V=5 in 760nm 18% band HLC
Planet rate	0.020		ph/s/psf	50 ppb, 300 mas (0.027 ppb/noise in counts after full integration)
Zodi rate	0.001		ph/s/psf	
PSF area	26.500		pixels	
Total photons	0.030		ph/s/psf	
Peak QE	0.571		e/ph	T-e2v data
Gain	**2500.000**		**e/e**	
Read noise@10MHz	100.000		e	
Read noise@100kHz	10.000		e	
Dark	1.500	2.000	c/px/hr	
CIC	0.018		c/px/frame	A function of gain
Frame time	**80.000**		**s**	
Total exposure	252000.000		s	100 hours 70%
Frames	3150.000		fr	
Planet photons	5040.000		ph/psf	
Total Photons in frame	0.091		ph/px/fr	
Total Photons in integration	285.283		ph/px	
Coincidence factor εCl	0.975			Fraction of counts not obscured by coincidence
Threshold factor εPC	0.819			Fraction of counts above photon counting threshold
Cosmic ray factor εCR	0.855			Fraction unpolluted by cosmic rays
Hot pixel factor εHP	1.000	0.950		Fraction of hot pixels that meet the DC requirement at EOL
Charge transfer factor εCTE	1.000	0.860		Fraction of signal read from CCD at EOL
Dark counts	105.000	140.000	c/px	
CIC counts	58.094		c/px	
PC mode planet counts	1964.104	1604.673	c/psf	
PC mode total counts	111.176	90.831	c/px	
PC mode dQE	0.390	0.318		Coincidence, threshold, cosmic rays (+ hot pixels, CTE)
PC mode detector noise (σ2)	2.330	2.830	c/px/hr	
PC mode total noise (σ)	85.253	87.501	c/psf	
PC mode SNR	**23.038**	**18.339**		
Analog mode planet counts	2105.437	1405.356	e/psf	No threshold or coincidence effect in analog mode
Analog mode total counts	139.332	113.834	e/px	
Analog mode dQE	0.488	0.399		Cosmic rays (+ hot pixels, CTE)
Analog mode detector noise (σ2)	4.732	5.732	c/px/hr	
Analog mode total noise (σ)	127.130	129.096	c/psf	
Analog mode SNR	**16.561**	**10.886**		
Conventional mode (10MHz) planet counts	2877.840	2351.195	e/psf	No threshold or coincidence or cosmic ray effect in conventional mode
Conventional mode (10MHz) total counts	162.897	133.087	e/px	
Conventional Mode (10MHz) dQE	0.571	0.467		QE only (+hot pixels, CTE)
Conventional mode (10MHz) detector noise (σ2)	80.179	80.179	c/px/hr	
Conventional mode (10MHz) total noise (σ)	28892.190	28892.192	c/psf	Unity gain
Conventional mode (10MHz) SNR	**0.100**	**0.081**		
Conventional mode (1MHz) planet counts	2877.840	2351.195	e/psf	No threshold or coincidence or cosmic ray effect in conventional mode
Conventional mode (1MHz) total counts	162.897	133.087	e/px	
Conventional Mode (1MHz) dQE	0.571	0.467		QE only (+hot pixels, CTE)
Conventional mode (1MHz) detector noise (σ2)	8.020	8.020	c/px/hr	
Conventional mode (1MHz) total noise (σ)	2890.699	2890.722	c/psf	Unity gain
Conventional mode (1MHz) SNR	**0.996**	**0.813**		

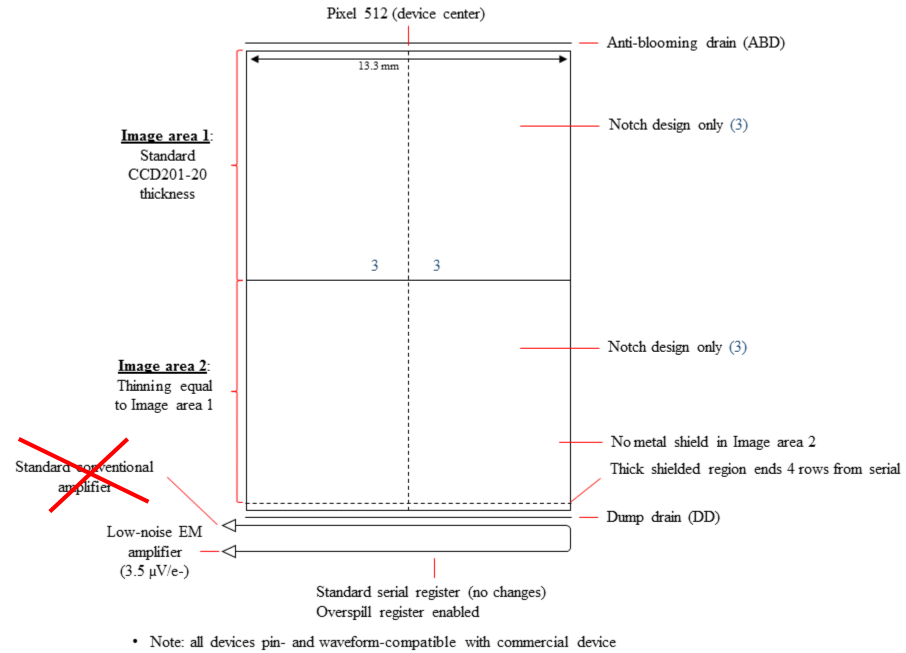
Top level engineering requirements

With gain

Without gain

EMCCD Technology Development





Type B investigates notch and narrow channels in the image area to address displacement damage resulting from space radiation.

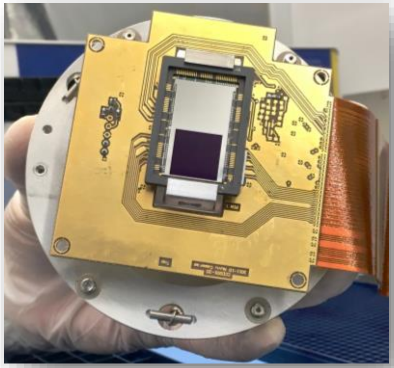
Type C has a notch channel (considered low risk) in the image area but adds a new amplifier and a gain register "overspill" to mitigate the effects of cosmic rays.

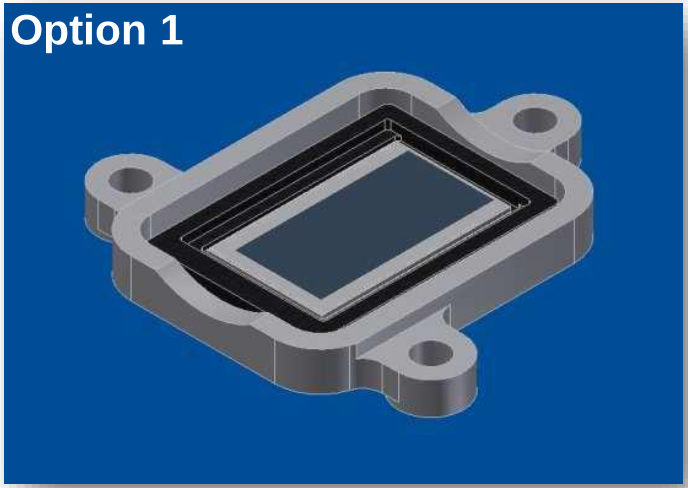
EMCCDs with these designs are scheduled for delivery in October 2018

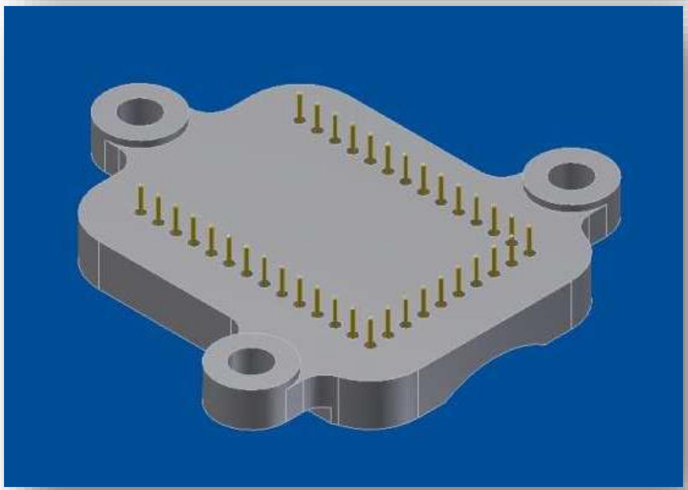
Package Options

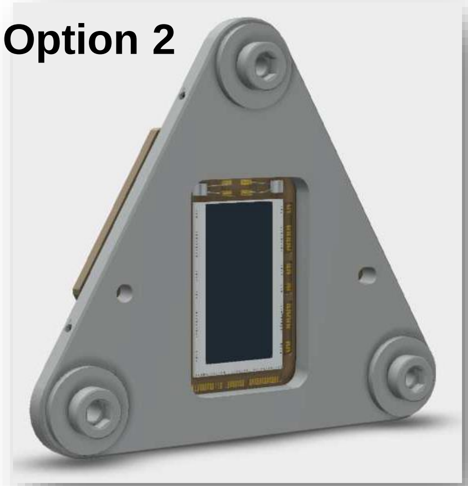
Option 1:
- Mounted commercial package
- Low risk
- Might not work

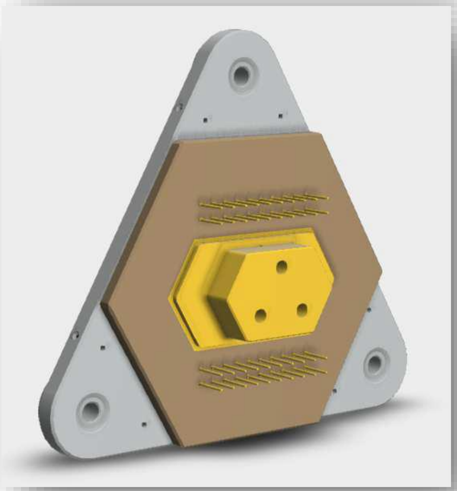
Option 2:
- New design
- Concept only
- Mechanically superior











EMCCD Technology Schedule

2018 Q12019

- RCV Type A sensors
- Radiation A Test at Loma Linda
- Package Flatness Test at Teledyne-e2v
- LOWFS demo
- Type A Post Rad Evaluation
- RCV Type B&C EMCCD
- Radiation B/C Test at Loma Linda
- Downselect for Flight 3/31/19

By the time of the downselect we must be certain about the requirement for the low speed conventional amplifier (and everything else!)

Path to Flight

- The camera team will be implementing a series of experiments in 2018 and beyond with the projector system to study relevant detector backgrounds in as flight-like a manner as possible.
  - Science team input would be valuable to help guide the experiments and explore the results
- Downselect of the flight detector design (possibly with different designs for LOWFS and science) is planned for Q1 2019
  - An observing plan with anticipated fluxes, observing times, and assigned detector modes will be essential to make an informed choice.

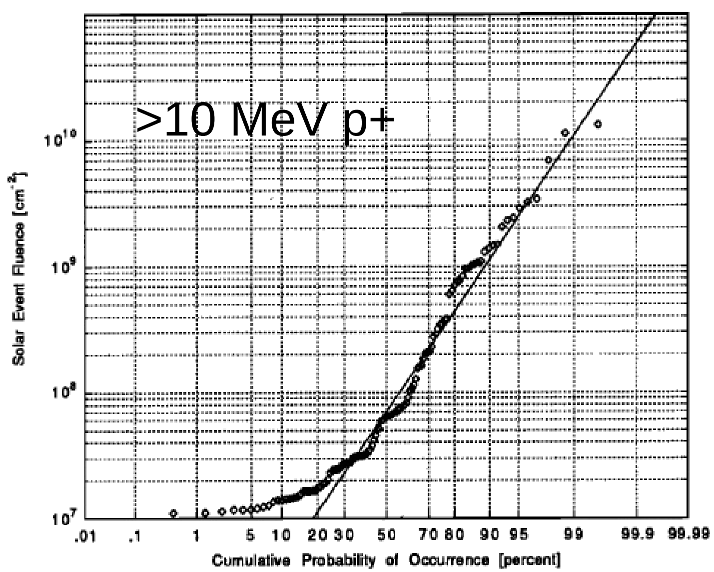
Thanks for your interest in CGI cameras!

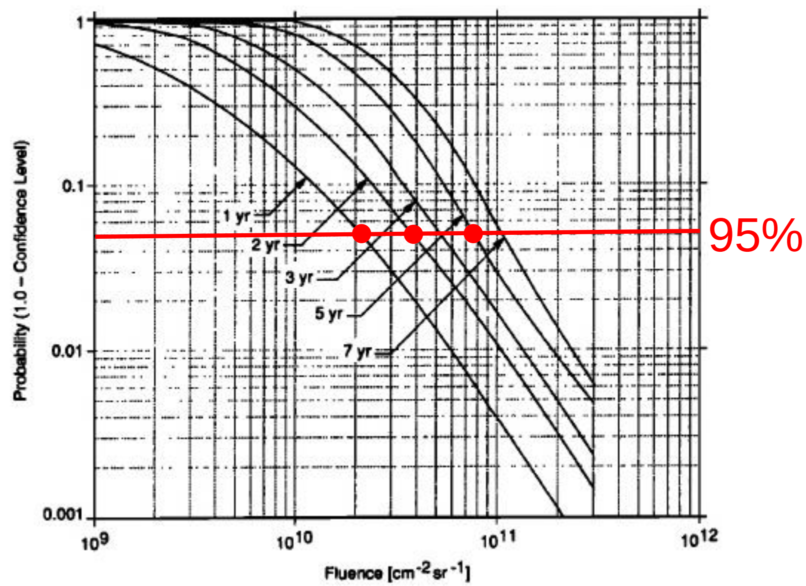
Backup

The L2 Environment

- **L2 is ~235 Earth radii away (the Moon is 60). It is far outside the influence of our protective magnetic field (~10Re).**
  - Inside the magnetic field (LEO, Geo), radiation exposure is dominated by energetic trapped particles. The exposure occurs regularly and is fairly predictable (HST).
  - Outside the magnetic field, radiation exposure is dominated by solar flares. These occur with a log-normal intensity distribution and with frequency determined by the 11 year solar cycle. The timing is impossible to predict except in statistical terms.

Feynman JGR 1993: Solar Proton Measurements 1963-1991



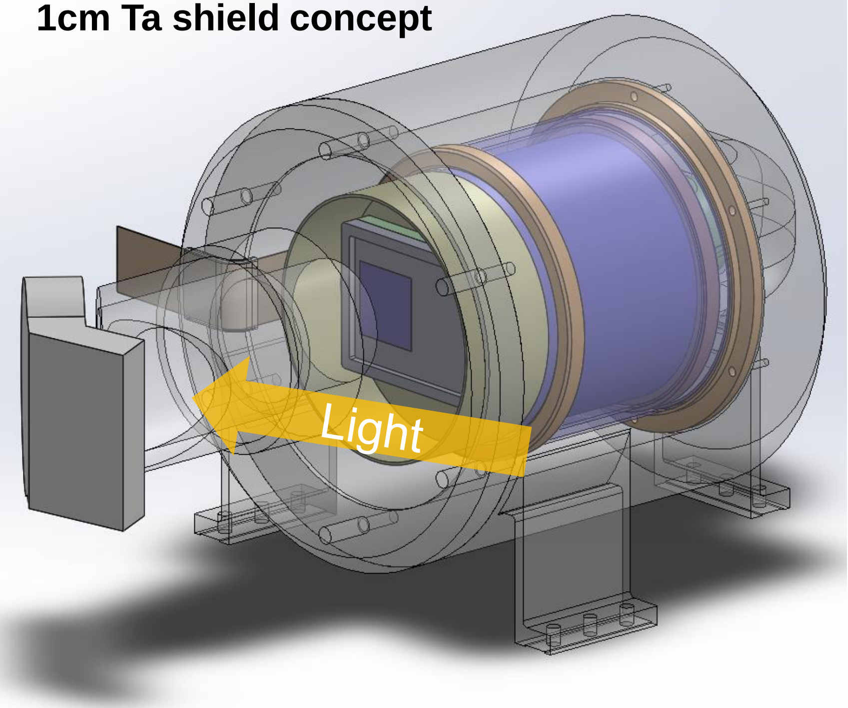


JPL standard practice is to test to 95% confidence in recognition of the observation that the dose is likely to be dominated by just a few events over the mission.

Camera Shield Design

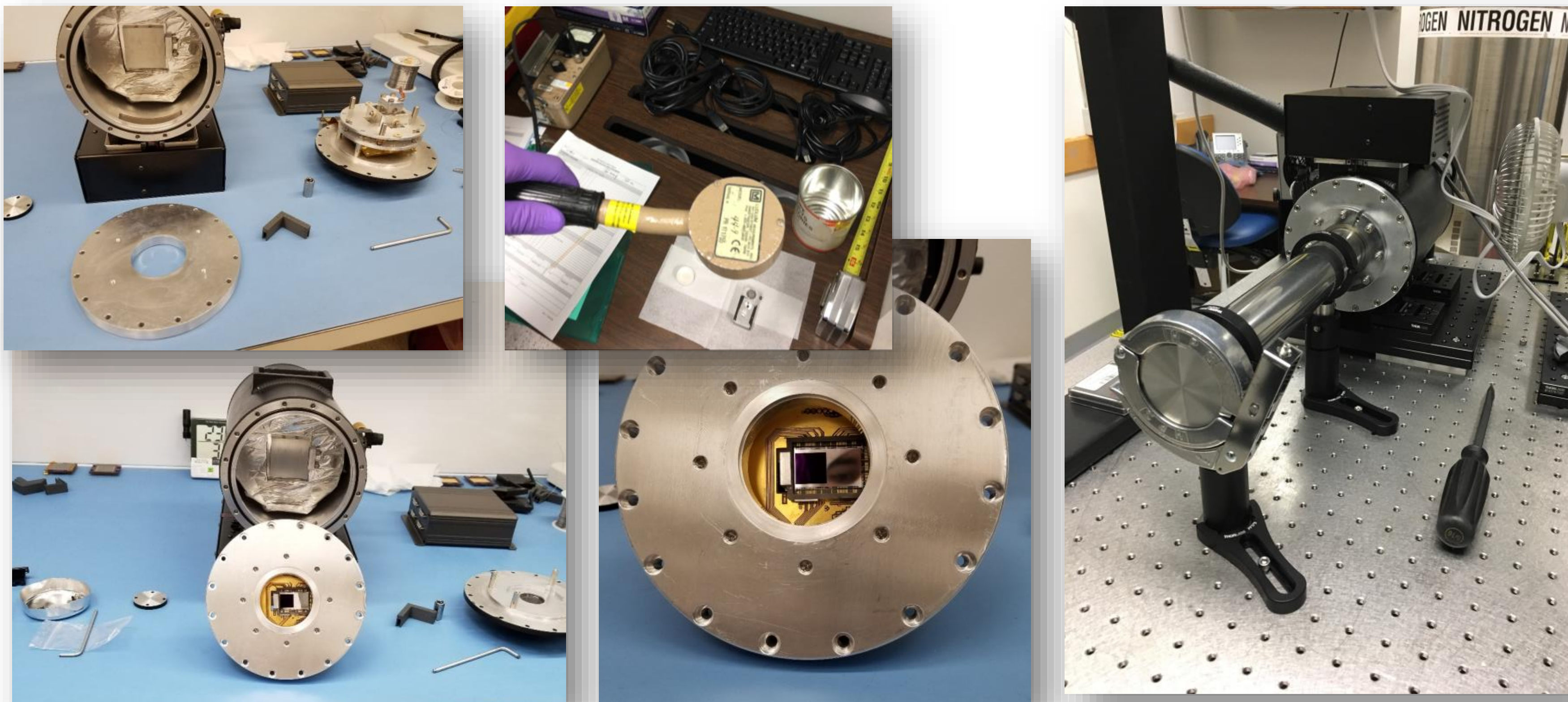
- All CCDs are sensitive to radiation damage because efficient charge transfer requires high purity silicon.
- We are designing a 5 kg, 1 cm thick tantalum shield (16.4 g-cm^{-3}) to protect the EMCCD as much as possible within the mass and volume allocations allowed.
- The shield will protect the EMCCD from the brunt of solar flares with particle energies typically up to the 100 MeV range
  - Nonetheless intense flares will cause the majority of detector damage.
- The shield will **not** protect the EMCCD from galactic cosmic rays. These ~GeV particles account for about 7% of the damage dose but are a 24/7 persistent nuisance to data quality due to the unusual response of the EMCCD to large signal pulses.
  - We assume 5 p-cm^{-2}-s^{-1} at L2 to estimate the effect on data (the CCD is 1.8 cm^2)

Completely enclosed,
1cm Ta shield concept



Fe55 testing

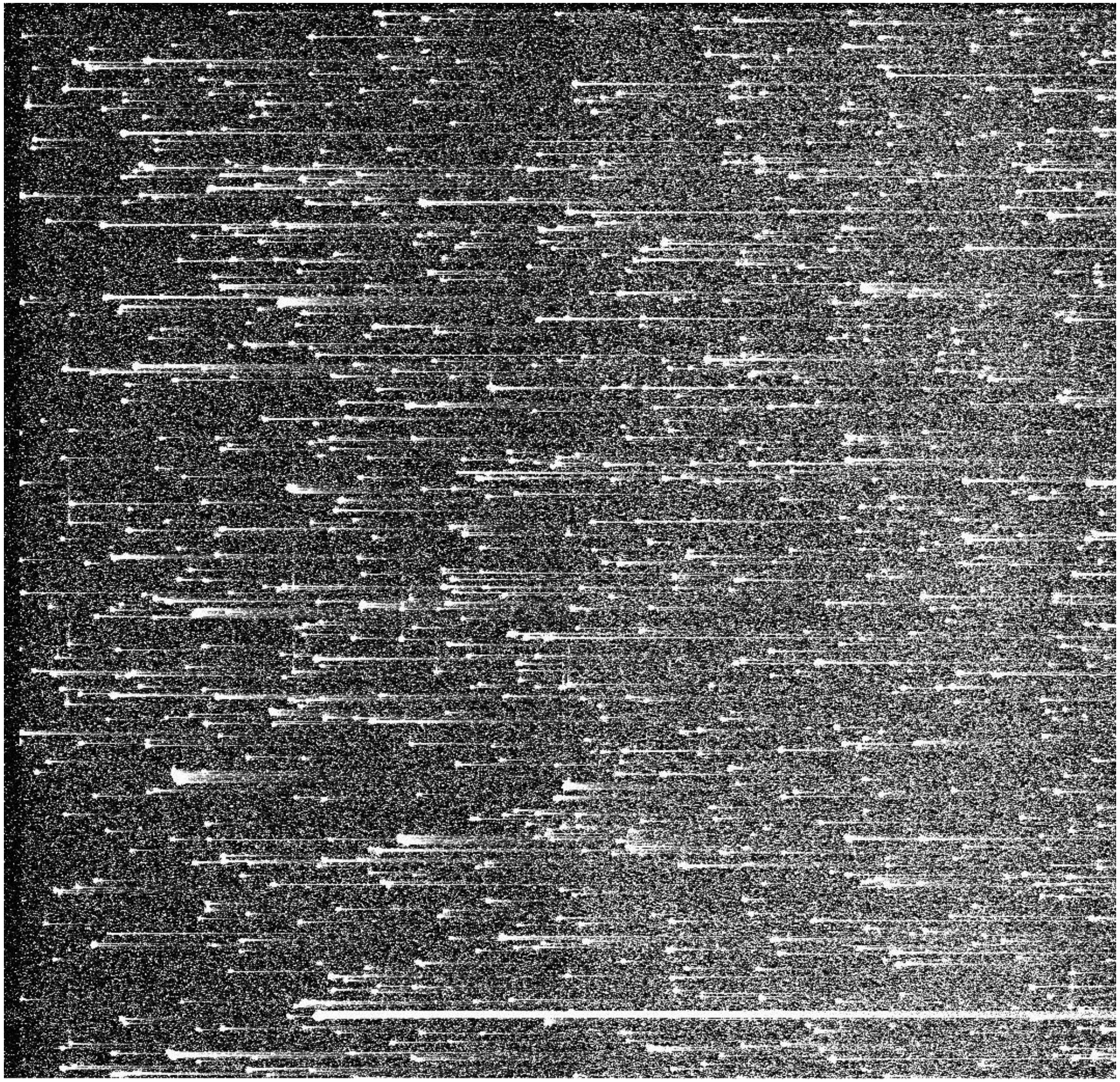
- **We have designed a new system to expose EMCCD sensors to Fe55 x-rays.**
  - Each Fe55 x-ray produces 1620e$^-$ in the EMCCD and can be used to track CTE as a function of trap damage.
  - The system can also be used with gain to simulate cosmic rays
  - We plan to merge to cosmic ray system with the projector to fully simulate images with an L2-like cosmic ray background.



100s at L2

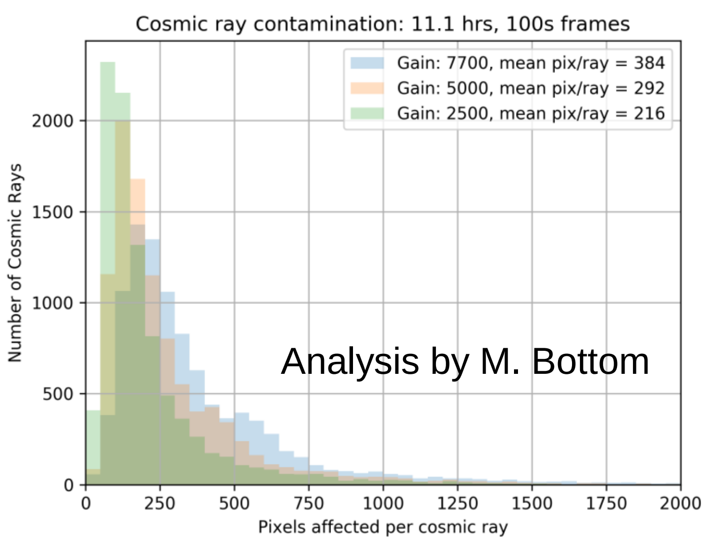
This is a 4000s dark image taken with the EMCCD in the lab. These are natural cosmic rays secondaries (muons). We believe the image contains about the same number of cosmic rays as will be detected in 100s at L2. If we fly the commercial sensor, then cosmic rays will be expected to look like this at beginning of life.

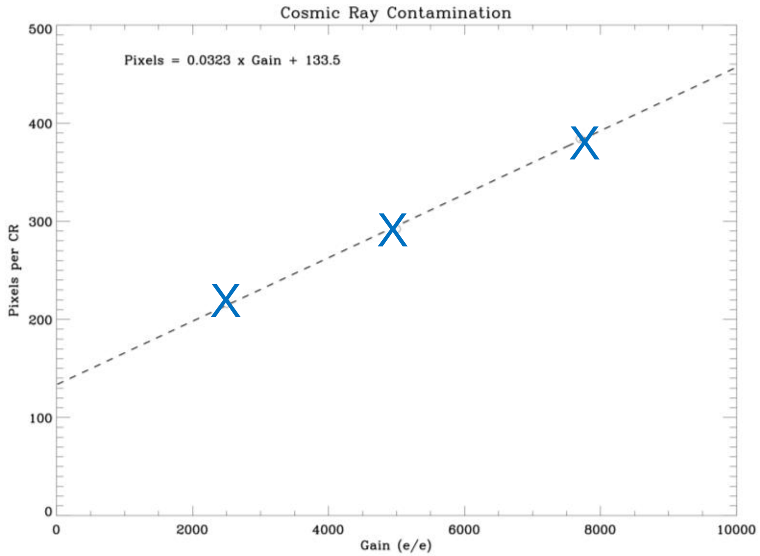
1) We're going to try to fix it
2) We will investigate whether post processing can effectively subtract the tails and reveal the science counts hiding underneath.



Cosmic Ray Tails

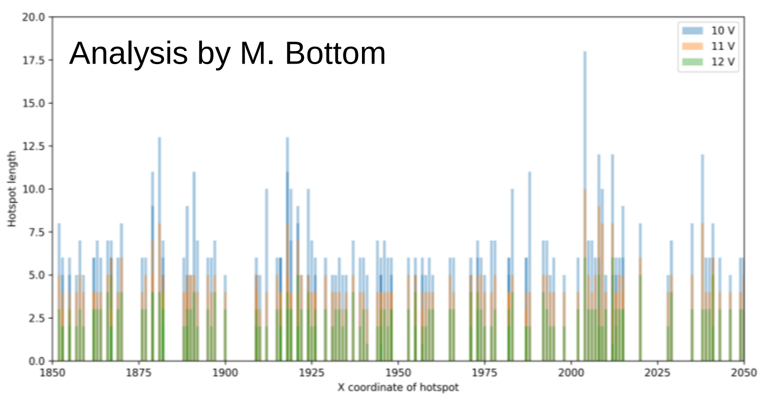
- Cosmic rays have an unusual response in the EMCCD. They develop a tail in the gain register because they contain a large amount of charge.
- We have evaluated the cosmic ray tail and determined the mean number of pixels above the photon counting threshold.
- We find the tail length is linearly proportional to the gain
- A test device with an "overspill" in the gain register designed to reduce the total charge is expected to arrive in late 2018.

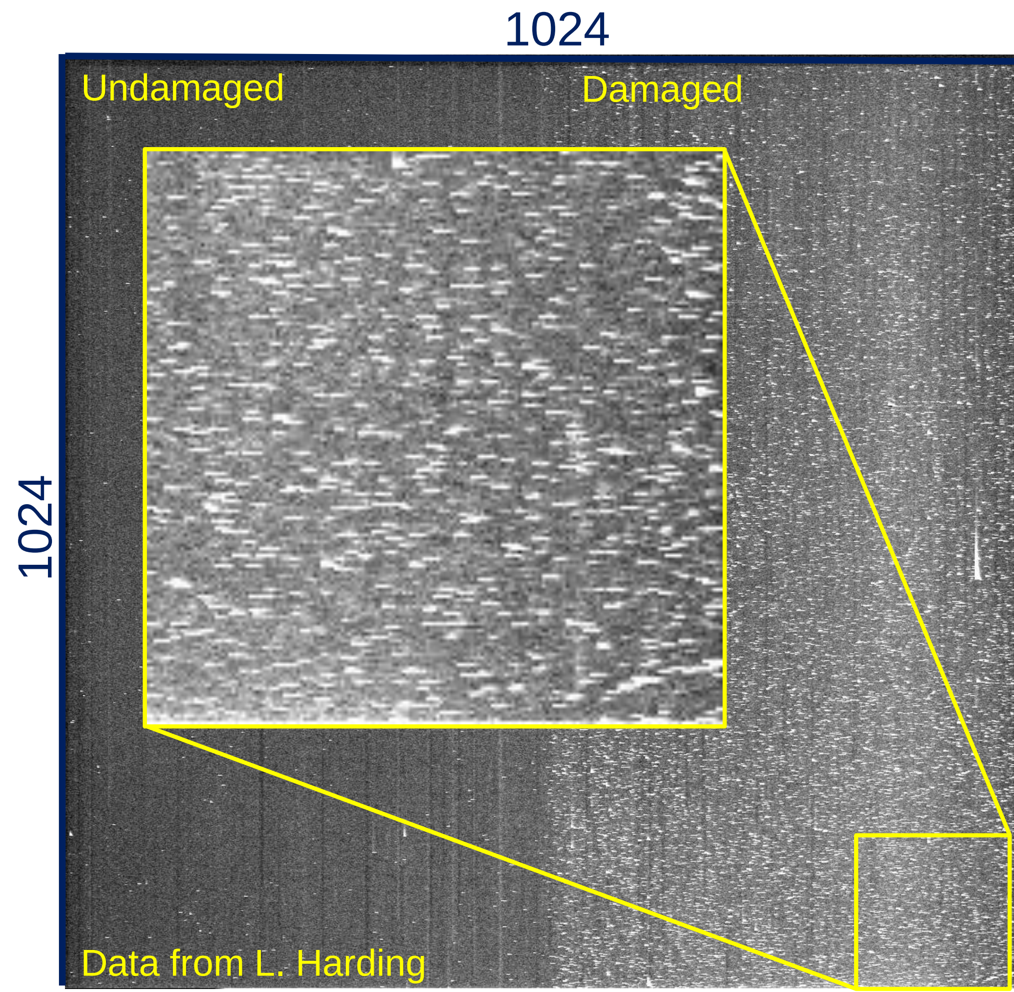




Radiation Damage I: Dark Current

Fraction of Pixels Below Threshold (10V Serial, 16 hours)		
Dark (e^- pixel^{-1}-hour^{-1})	Undamaged	Damaged
0.5	27.4%	2.3%
0.75	46.9%	6.1%
1.0	66.9%	13.3%
2.0	98.8%	67.6%
3.0	100%	95.8%

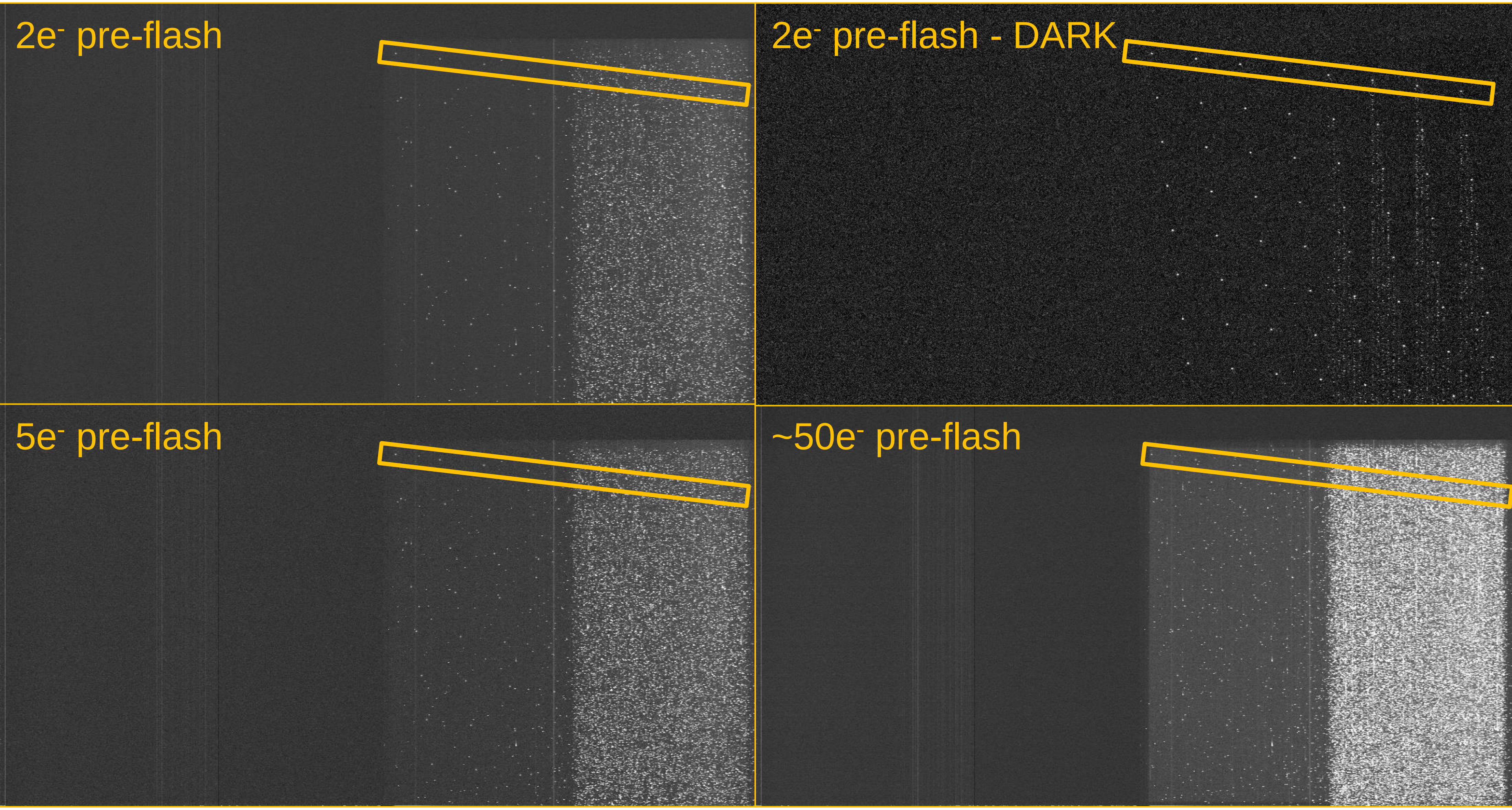




This is a ~day long photon counted dark integration. It shows a population of hot pixels that we believe represents end-of-mission. Notice that the hot pixels are stretched in the serial direction, and the amount of stretch is determined by the serial drive voltage.

Radiation Damage II: Background Stability

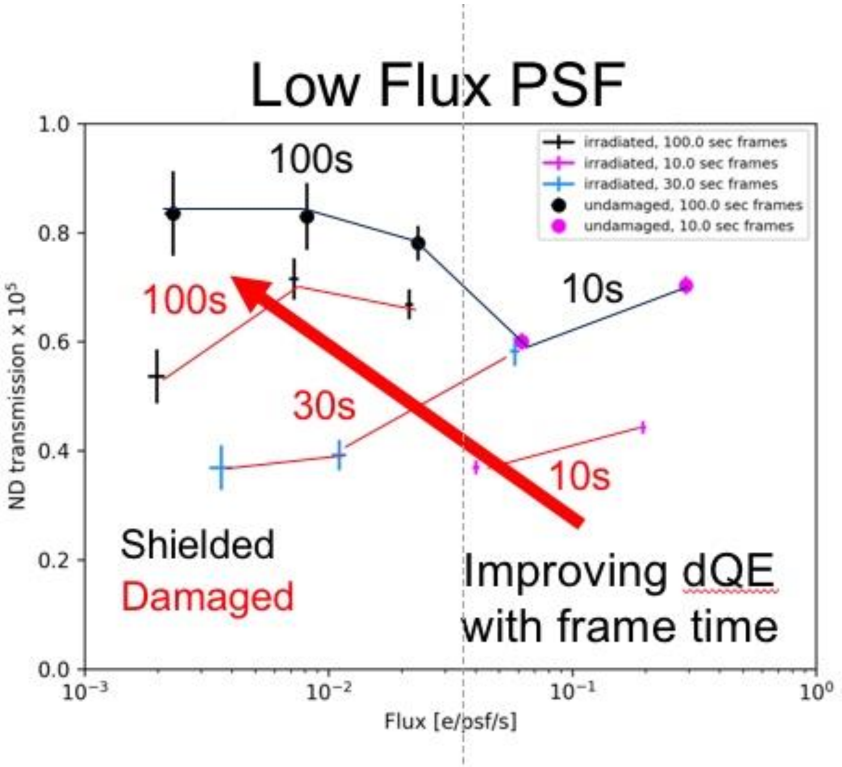
24 hour integration with 10s frames



Undamaged Damaged Undamaged Damaged

Radiation Damage III: Charge Transfer

- We image a ~3 pixel PSF onto the EMCCD at a number of different locations
- The brightness is measured without gain in a few second exposure.
- We insert an ND5 filter into the path and measure again in photon counting mode (~days depending on the flux).
- **The ratio between the two measurements (the filter transmission) should not change, yet it does change at low fluxes.**
- This is an expected effect of charge trapping ("CTE") in the detector and has been observed before (cf HST WFC3 handbook).
- We can mitigate this effect to some degree by lengthening the exposures to build up a background in the image that fills the traps. This is the reason we anticipate 80-100s frames.
- **We anticipate improved data this year using our projector system to test new sensors.**

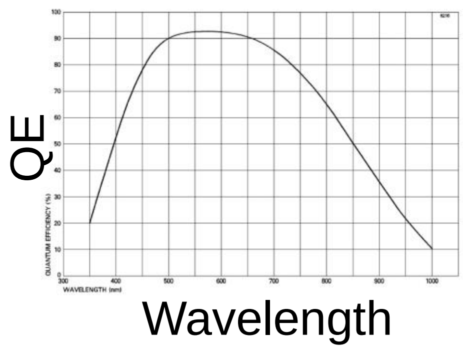


dQE: Photon Counting Sensitivity

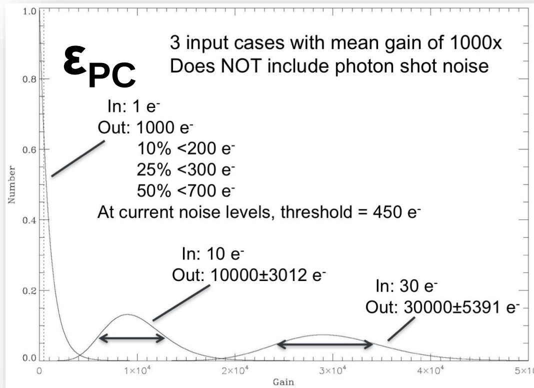
$$dQE = QE \times [\varepsilon_{PC} * \varepsilon_{CR}] \times [\varepsilon_{HP} * \varepsilon_{CTE}]$$

These factors evolve with radiation exposure

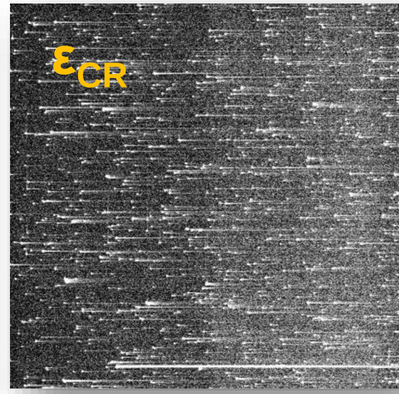
=



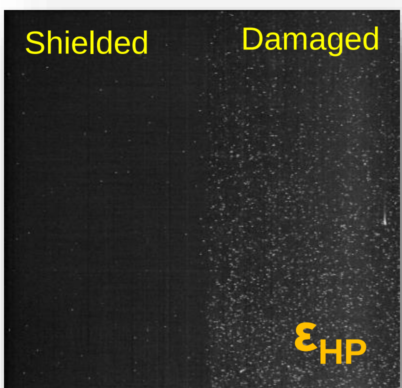
x



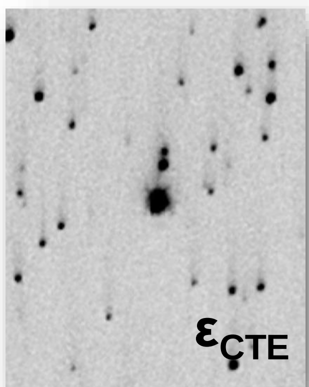
x



x



x

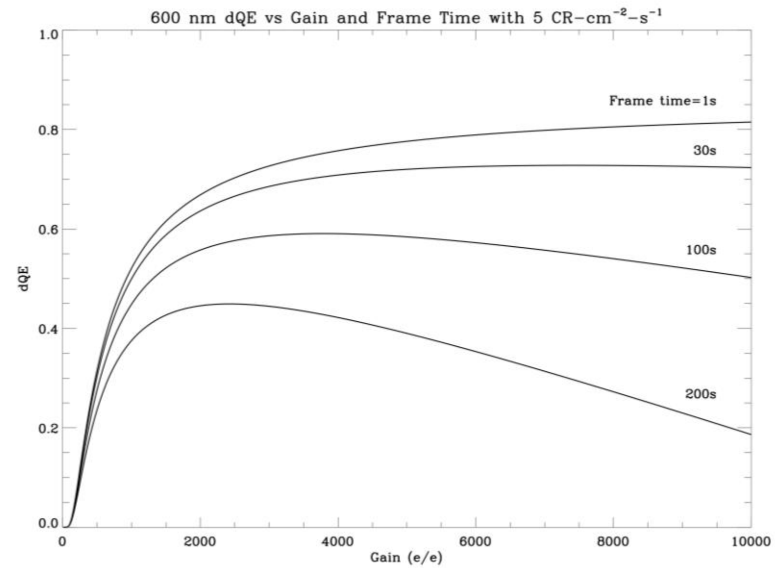


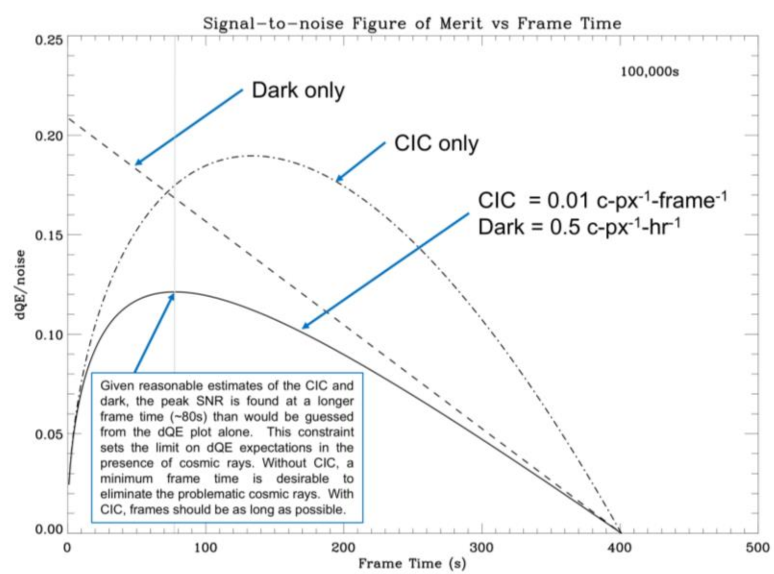
Our program is actively working on optimizing all of these factors to maximize performance.

Data courtesy L. Harding

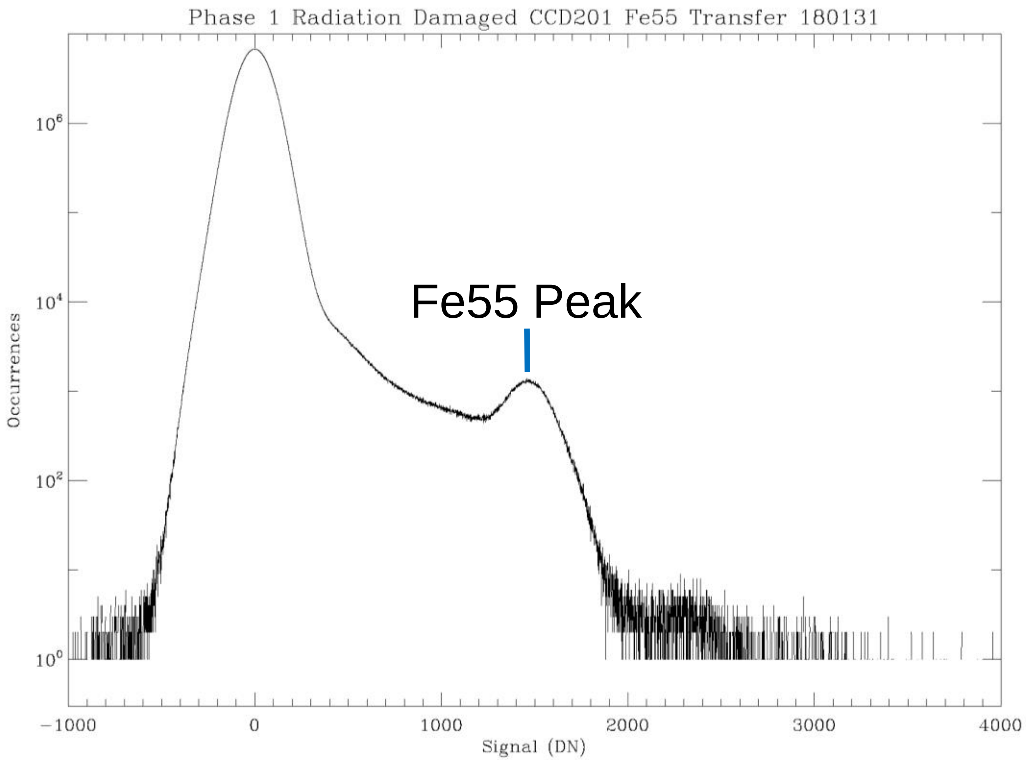
Performance Simulations

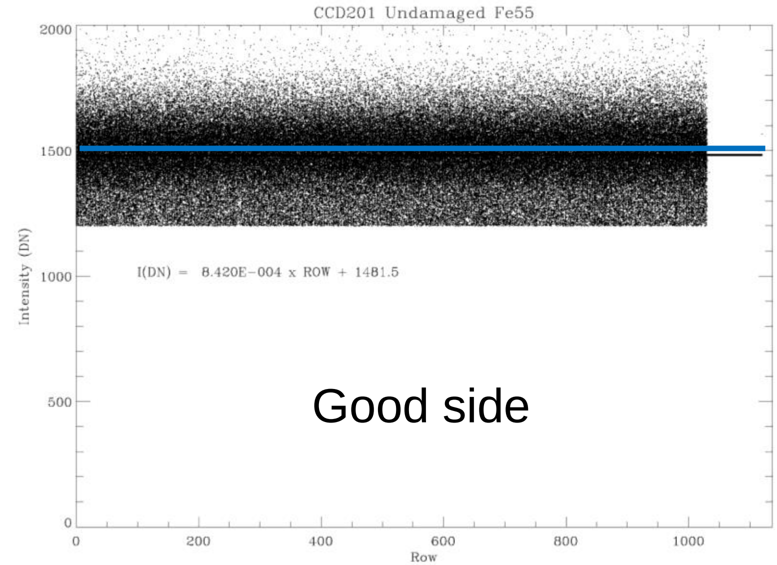
- **The dQE terms have functional dependence on gain and frame time that allows us to explore the optimal operating conditions at L2.**
- **The upper right plot shows dQE (beginning of life) as a function of gain.**
  - At low gain, dQE is reduced by photon counting threshold losses
  - At high gain, dQE is increasingly affected by cosmic rays.
- **The lower right plot shows dQE/noise, a proxy for the optimal signal-to-noise condition, as a function of frame time.**
  - Short frame times are dominated by CIC
  - Long frame times are increasingly obscured by cosmic rays
  - The peak signal-to-noise condition *for the commercial sensor* is at a gain of ~4000x and with a frame time of 80s.

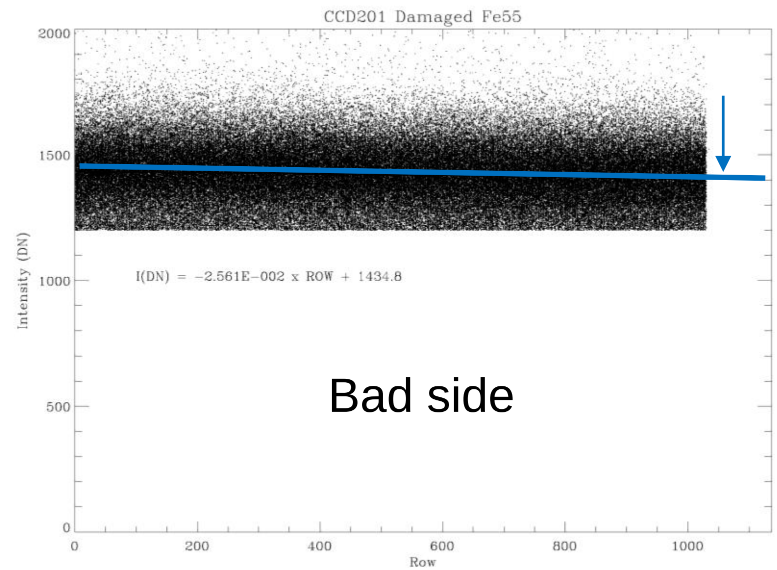




Commercial Sensor Fe55 Results







Jet Propulsion Laboratory
California Institute of Technology

jpl.nasa.gov